Spatial distributions and temporal variations of the near-surface soil freeze state across China under climate change

Xiqiang Wang[a,b], Rensheng Chen[a,*], Guohua Liu[a,b], Yong Yang[a], Yaoxuan Song[a], Junfeng Liu[a], Zhangwen Liu[a], Chuntan Han[a], Xiaojiao Liu[a,b], Shuhai Guo[a,b], Lei Wang[a,b], Qin Zheng[a,b]

[a] Qilian Alpine Ecology and Hydrology Research Station, Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

ABSTRACT

The near-surface soil freeze state is affected by global warming, and its changes have profound effects on landscapes, ecosystems and hydrological processes. On the basis of daily soil freeze observational data at 476 meteorological stations over 50 freezing years from September 1, 1961 to August 31, 2011, the spatial distributions and temporal variations of the near-surface soil freeze state were estimated using five freeze variables (first date, last date, maximum seasonally frozen depth, duration and actual number of freeze days) across China, which was divided into three regions (eastern China, northwestern China and the Qinghai-Tibetan Plateau (QTP)). The near-surface soil freeze state varied greatly across China. The QTP has an earlier freeze, later thaw, longer freeze days and deeper seasonally frozen depth than the other two regions. The spatial distributions of the near-surface soil freeze state can be explained largely by altitude in northwestern China and on the QTP, whereas they can be explained by latitude in eastern China. The near-surface soil freeze state has changed significantly over 50 freezing years. On average across China over the study period, the first date of freezing was delayed by approximately 10 ± 1 days with a rate of 0.20 ± 0.02 days/year, the last date advanced by approximately 18 ± 2 days with a rate of 0.36 ± 0.04 days/year, the duration and the number of freeze days decreased by 28 ± 2 and 23 ± 2 days with rates of 0.56 ± 0.04 and 0.45 ± 0.04 days/year, respectively, and the maximum seasonally frozen depth decreased by 20 ± 3 cm with a rate of 0.41 ± 0.06 cm/year. The change in the freeze variables is relatively large in high-latitude and high-altitude regions.

1. Introduction

Global warming, caused by anthropogenic greenhouse gas emissions, significantly changes the cryosphere (IPCC, 2014), and these changes serve as indicators of climate change. Frozen ground is an important component of the cryosphere, consisting of permafrost and seasonally frozen ground (SFG). Permafrost is defined as ground with the temperature remaining at or below 0 °C for two or more consecutive years (Dobinski, 2011), and it occupies almost a quarter of the exposed land surface in the Northern Hemisphere (Zhang et al., 1999), whereas SFG occupies approximately 57% in the Northern Hemisphere (Zhang et al., 2003). Under the warming climate, significant degradation of frozen ground has been detected in permafrost regions and SFG regions (IPCC, 2014). Changes in the near-surface soil freeze state, including SFG and the active layer above the permafrost, will have profound

effects on landscapes, ecosystems and hydrological processes because almost all ecological, hydrological, pedological and biological activities occur within this seasonal soil freeze layer (Cuo et al., 2015; Hinzman et al., 1991; Peng et al., 2016; Zhao et al., 2004). For example, the near-surface soil freeze state affects the moisture exchange between the atmosphere and the ground, the infiltration ability, hydraulic conductivity, and permeability; it also affects surface water and ground-water quantitative shifts (Cheng and Jin, 2013; Cherkauer and Lettenmaier, 1999; Connon et al., 2014; Cuo et al., 2015; Karlsson et al., 2012; McCauley et al., 2002). Changes in the near-surface soil freeze state can influence the growth of vegetation (Zhou et al., 2015), and they can also have an important effect on carbon exchange between the atmosphere and the ground (Mu et al., 2015; Wang et al., 2014; Zimov and Chapin, 2006).

Under the warming climate, significant efforts have been devoted to

---

* Corresponding author at: Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, 320 West Donggang Road, Lanzhou 730000, China.
  E-mail address: crs2008@lzb.ac.cn (R. Chen).

research on the near-surface soil freeze state, ranging from regional to national to hemispheric scales by using remote sensing or in situ observations. The active layer above the permafrost has been determined to thicken significantly in high-latitude and high-altitude regions (Akerman and Johansson, 2008; Fyodorov-Davydov et al., 2008; Mazhitova, 2008; Wu and Zhang, 2010; Zhao et al., 2010). However, less research has focused on SFG regions, despite their large area and importance (Frauenfeld and Zhang, 2011; Frauenfeld et al., 2004; Wang et al., 2015; Zhang et al., 2003). Although several studies have focused on the changes in the near-surface soil freeze state, such as the changes in the freeze-free period across Germany (Menzel et al., 2003), the number of freeze days across Canada (Henry, 2008) and in Indiana, USA (Sinha and Cherkauer, 2008), the first and last freeze dates across Kansas, USA (Anandhi et al., 2013), the timing and duration of the near-surface soil freeze status across China (Wang et al., 2015), the mean annual (monthly) area extent of the seasonal soil freeze state across China (Peng et al., 2016), and the maximum seasonally frozen depth across Eurasian high latitudes (Frauenfeld and Zhang, 2011) and China (Peng et al., 2017; Wang et al., 2009), these studies estimated the distributions and variations of the near-surface soil freeze state mainly from the soil temperature and the air or ground surface temperature, which may not correspond to the 'true' soil freeze state. The near-surface soil freeze state depends not only on the air temperature, but also on the warm season precipitation, cold season snow cover, and site-specific soil properties (Frauenfeld and Zhang, 2011).

On the basis of daily soil freeze observational data from the standard frost tube, the near-surface soil freeze state was estimated on the QTP (Zhao et al., 2004) and in the Three Rivers Source Region in China (Luo et al., 2017). However, due to the lack of long-term observational data, related research at local and regional scales is still insufficient. A comparative study of different estimation methods has not been conducted to date. Under the warming climate, frozen ground degradation has occurred widely in most of China (Cheng and Jin, 2013; Jin et al., 2007), and understanding the spatial distributions and temporal variations of the near-surface soil freeze state has substantial social, economic and ecological significance. The primary aims of this study are to (1) analyse the spatial distributions of the first date (FD), last date (LD), duration (DR), actual number of freeze days (NF) and maximum seasonally frozen depth (SFD) across China over 30 freezing years from September 1, 1961 to August 31, 1991, as well as the spatial distribution characteristics of these five variables for the three frozen ground regions in China, and (2) estimate the temporal variations of the near-surface soil freeze state across China over 50 freezing years. The results of this study will provide an important reference for analysing, contrasting and predicting the changes of the near-surface soil freeze state under the warming climate.

2. Data and methods

The daily soil freeze observational data at 476 meteorological stations across China were collected from the China Meteorological Administration (CMA). Most of these 476 stations are located in eastern China, with fewer stations being located in western China, especially in high-altitude regions (Fig. 1). The seasonally frozen depth is measured once a day at 08:00 Beijing Time during the freezing period by reading the upper and lower depths of the distilled water contained in standard frost tubes that were buried in the soil. According to the general freezing state of the meteorological stations, the CMA installed different standard frost tubes, the lengths of which vary from 50 cm to 450 cm. The earliest station observations date back to 1955. A number of station observational records end around the 1990s, and others are available through 2011. The lengths of the records vary, with the longest being 57 years, and the shortest being only 1 year.

Strict data quality control is necessary because a number of meteorological stations changed locations or were removed, a number lack large amounts of observational records, and a number exceed the

maximum range of the standard frost tubes. According to the statistics, there were nearly 295 years (50% of these years were around the 1960s) and 81 stations (mainly distributed in the north of the Xinjiang Uygur Autonomous Region, the north and south of Qinghai Province, and the north of the Inner Mongolia Autonomous Region) of freezing depth exceeding the maximum range of the standard frost tubes. For each station, the freezing year with complete daily records was reserved to analyse the near-surface soil freeze state. For the maximum seasonally frozen depth, the years exceeding the maximum range of the standard frost tubes were not considered. In general, the similarity of the geographic and climatic features was considered when moving the meteorological stations (Peng et al., 2016; Peng et al., 2017; Wang et al., 2015). Therefore, we assume that station movement had little effects on our study.

Referring to the ground meteorological observation standard of the CMA (CMA, 2003) and considering that most of China begins to freeze during the early fall, we defined the freezing year (hereafter referred to as year) to begin on September 1st of the current year and end on August 31st of the following year. After strict data quality control, the station numbers for each available year varied greatly. To reduce the deviation of the available station numbers for each year, we choose 1961 as the beginning year in this study. The station numbers range from 324 stations in 1961 to 420 stations in 2011 with an average of 382 stations (Fig. 2). In this study, the first date (FD) and last date (LD) of the soil freeze are defined as the first date after September 1st and the last date before August 31st across the year when the daily freeze thickness is not zero, respectively. The days between the first and last date are defined as the duration (DR) of the soil freeze. Due to discontinuous freezing events during the period between the first and last dates, we further defined the actual number of freeze days (NF) by counting the number of days when the daily freeze thickness was not zero. For each station, the FD, LD, DR, NF and SFD of the near-surface soil freeze state were calculated for each year.

To reveal the spatial distributions of the near-surface soil freeze state, the long-term mean values of five freeze variables were calculated over 30 years from September 1, 1961 to August 31, 1991. Not all of the meteorological stations have complete soil freeze data in this study. Fewer missing years (< 25% of the study period) are permitted in the calculation of the long-term mean values of the five freeze variables (Jones and Hulme, 1996; Wang et al., 2015). Therefore, the stations with at least 22 years of records were used to calculate the long-term mean values. There are 351 stations for calculating the long-term mean values of the five freeze variables for all of China, 242 stations in eastern China, 60 stations in northwestern China, and 49 stations on the QTP (Fig. 3).

For each station, linear regression was used to estimate the change trend for the five freeze variables over the study period. Only those stations with > =38 years of records (missing years are < 25% of the study period) (Fig. 1) and passing the statistical tests at the $p < 0.1$ level were considered in this study. To investigate the regional average trend for the freeze variables across China, the anomalies of each variable were calculated over the study period after removing the long-term average (September 1, 1961 through August 31, 1991) for each station, and then all stations were composited to structure an averaged time series for the anomalies of each variable. Linear regression was used to estimate the regional average trend for the anomalies of each variable across China, as well as the three frozen ground regions. To investigate the geographic characteristics of the near-surface soil freeze state, a correlation analysis between the linear trends of the freeze variables and latitude (altitude) was also conducted in this study.

3. Results

3.1. Spatial distributions of the near-surface soil freeze state

From the long-term mean values of five freeze variables over
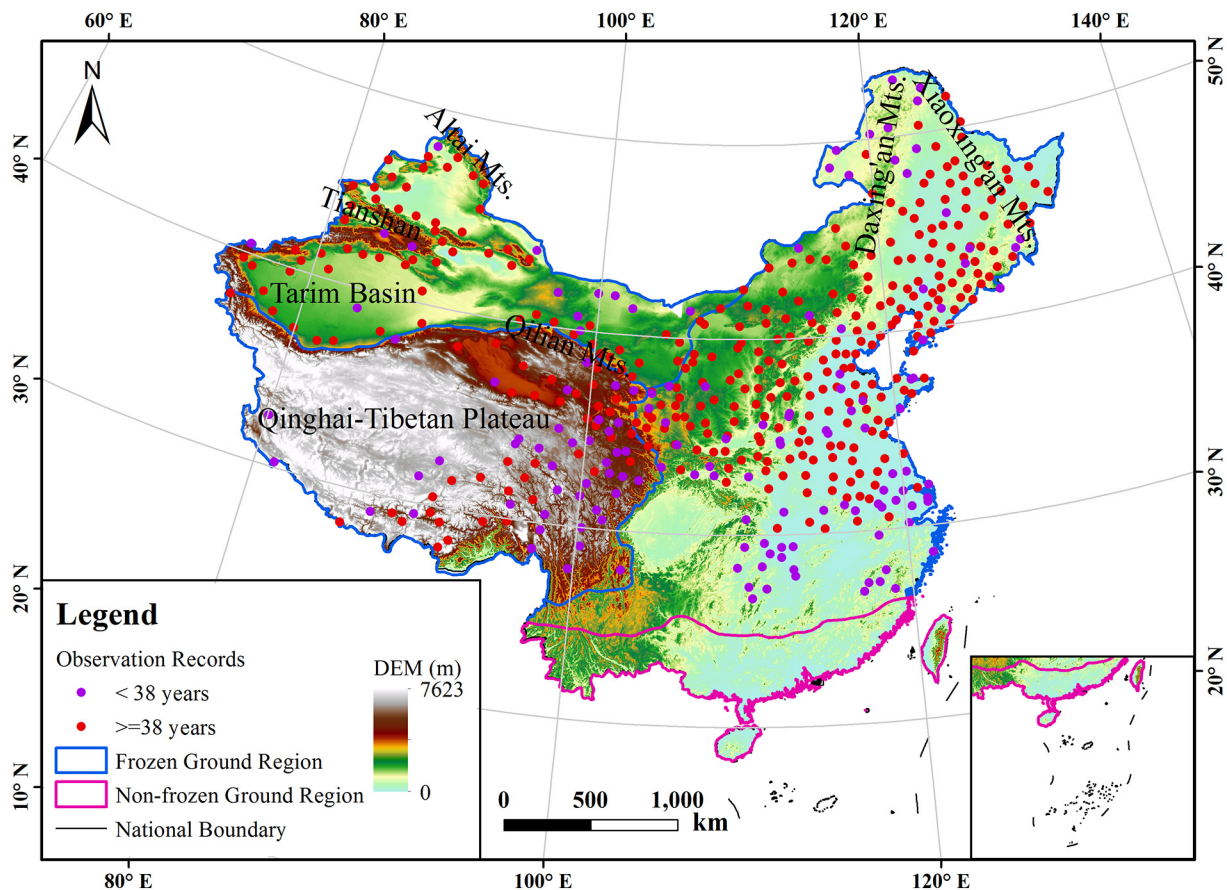
Fig. 1. Location of the near-surface soil freeze observational stations and three frozen ground regions across China in this study. Included are the 476 observational stations and the available soil freeze data over 50 freezing years from September 1, 1961 to August 31, 2011, with red dots representing data availability of > =38 years, and purple dots representing data availability of < 38 years. The three frozen ground regions across China are (A) in eastern China, (B) in northwestern China, and (C) on the QTP (Zhou et al., 2000). The boundary of the three frozen ground regions was derived from the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn).The background reflects the altitude and the main terrain distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
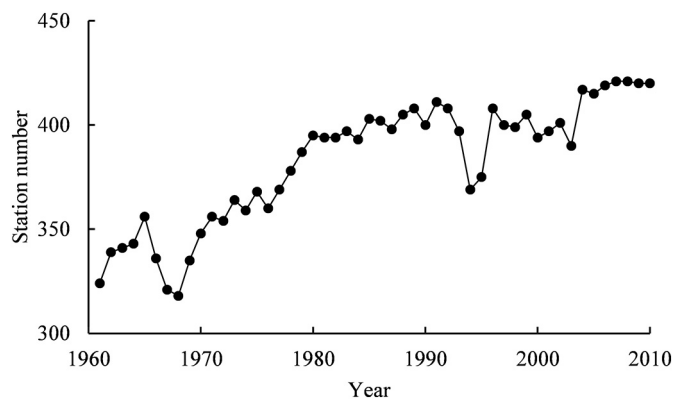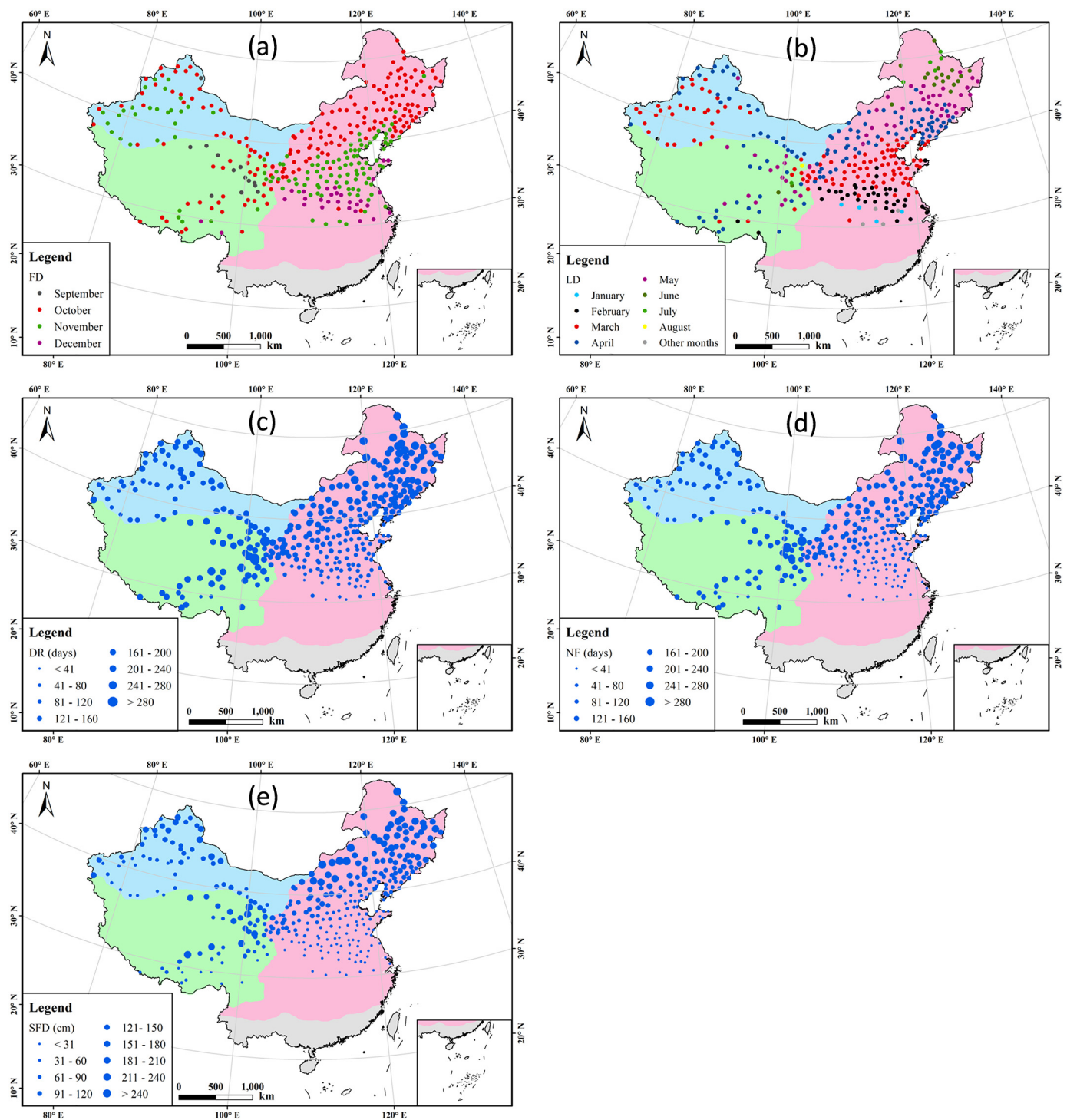

Fig. 2. Number of the near-surface soil freeze observational stations with available data for each year across China over 50 years (1961–2010).

30 years from September 1, 1961 to August 31, 1991, we found that the near-surface soil freeze state varied considerably across China (Table 1, Fig. 3).

In China, the near-surface soil generally began to freeze in the early fall (Fig. 3a), and the difference in the earliest and latest FD was nearly 103 days. The average FD was earlier on the QTP (45 ± 18 days) than in eastern China (67 ± 19 days) and northwestern China (56 ± 12 days) (Table 1). In eastern China, the freeze first began at the beginning of September from the current year until late December to

complete the entire process of freezing, which lasted nearly 103 days. The freeze first occurred in northeastern China such as in the Daxing'an and Xiaoxing'an mountains and was gradually postponed from north to south (Fig. 3a). The FD basically showed a zonal distribution in the northeast to southwest direction. In northwestern China, the earlier FD began in the northern mountain areas of Xinjiang such as the Altai Mountains, and the relatively late FD began around the Tarim Basin (Fig. 3a). On the QTP, the average FD was postponed from north to south, with the earlier freeze in the north of Qinghai Province and the later freeze in the south of the Tibetan Autonomous Region (Fig. 3a). Due to the high altitude, the FD for the QTP was nearly 34 days earlier than that in eastern China at the same latitude. The spatial distribution of the FD has a close relationship with latitude and altitude. The FD decreased approximately 3.2 days per degree of latitude in eastern China ($p < 0.01$) with $R^2 = 0.64$, implying that approximately 64% of the total variability in the FD can be explained by latitude. Similarly, the FD decreased approximately 0.8 days per 100 m of altitude in northwestern China ($p < 0.05$, $R^2 = 0.09$) and approximately 0.7 days per 100 m of altitude on the QTP ($p < 0.1$, $R^2 = 0.06$).

Similar to the FD, the LD exhibited evident regional diversity (Fig. 3b), and the difference in the earliest and latest LD was nearly 278 days. The average LD was later on the QTP (237 ± 31 days) than in eastern China (216 ± 40 days) and northwestern China (211 ± 17 days) (Table 1). In eastern China, the LD was postponed gradually from south to north. The latest LD occurred in the Daxing'an and Xiaoxing'an mountains and lagged for nearly 256 days behind the earliest one (Fig. 3b). In northwestern China, the earlier LD occurred

Fig. 3. Spatial distributions of the near-surface soil freeze state across China over 30 years (September 1, 1961 through August 31, 1991). (a), (b), (c), (d) and (e) represent the trend of the FD (first date), LD (last date), DR (duration), NF (actual number of freeze days) and SFD (maximum seasonally frozen depth), respectively. The background in figure reflects the three frozen ground regions and non-frozen ground region.

around the Tarim Basin, and the later LD occurred in the Altai, Qilian and Tianshan mountains (Fig. 3b). Compared with eastern China at the same latitude, the LD lagged for nearly 49 days on the QTP. The spatial distribution of the LD also has a close relationship with latitude and altitude. The LD increased approximately 7.8 days per degree of latitude in eastern China ($p < 0.01$, $R^2 = 0.83$), implying that approximately 83% of the total variability in the LD can be explained by latitude. Similarly, the LD increased approximately 2.0 days per 100 m of altitude on the QTP ($p < 0.01$, $R^2 = 0.16$).

The DR varied greatly across China, ranging from < 2 weeks in southern China through nearly 304 days. The average DR was longer on the QTP (192 ± 47 days) than in eastern China (149 ± 56 days) and northwestern China (155 ± 28 days) (Table 1). The largest DR span was in eastern China, with the shortest duration being only several days in southern China, and the longest duration being nearly 304 days in the Daxing'an and Xiaoxing'an mountains (Fig. 3c). In northwestern China, the shorter DR was found around the Tarim Basin with approximately 120 days, and the longer DR was found in the Altai, Qilian

Table 1
Long-term mean values of five freeze variables across China and the three frozen ground regions from 1961 to 1990.[a]

	FD (days)	LD (days)	DR (days)	NF (days)	SFD (m)
Eastern China	56 ± 12	211 ± 17	155 ± 28	135 ± 24	0.99 ± 0.41
Northwestern China	67 ± 19	216 ± 40	149 ± 56	126 ± 66	0.89 ± 0.68
QTP	45 ± 18	237 ± 31	192 ± 47	165 ± 56	1.01 ± 0.61
China	62 ± 19	218 ± 37	156 ± 53	133 ± 61	0.93 ± 0.63

[a] To facilitate comparison, the base date is September 1st, and the FD and LD values are the number of days after the base date.

and Tianshan mountains with > 150 days (Fig. 3c). Compared with eastern China at the same latitude, the DR was approximately 83 days longer on the QTP. The mean NF was 126 ± 66, 135 ± 24 and 166 ± 56 days in eastern China, northwestern China and on the QTP, respectively, which was significantly less than the mean DR due to the discontinuous freeze events during the freeze period (Table 1). Compared with eastern China at the same latitude, the NF was approximately 90 days longer on the QTP. The DR increased approximately 11.0 days per degree of latitude in eastern China ($p < 0.01$, $R^2 = 0.85$), approximately 1.5 days per 100 m of altitude in northwestern China ($p < 0.1$, $R^2 = 0.06$), and approximately 2.7 days per 100 m of altitude on the QTP ($p < 0.01$, $R^2 = 0.13$). The NF increased approximately 13.2 days per degree of latitude in eastern China ($p = 0.01$, $R^2 \leq 0.87$) and approximately 2.5 days per 100 m of altitude on the QTP ($p < 0.05$, $R^2 = 0.08$).

The spatial distribution of the maximum seasonally frozen depth showed that the higher SFD (> 2.0 m) was mainly located in northeastern and northwestern China and on the QTP. The lower SFD (< 0.1 m) was mainly found in southern China and the southeast margin of the QTP (Fig. 3e). The average SFD was 0.89 ± 0.68 m, 0.99 ± 0.41 m and 1.01 ± 0.61 m in eastern China, northwestern China and on the QTP, respectively (Table 1). In eastern China, the SFD was deeper in the north and shallower in the south and was basically distributed along the longitude, not completely parallel, but inclined towards the northeast-southwest direction (Fig. 3e). In northwestern China, locations with SFD < 0.8 m were found around the Tarim Basin, and a number of stations with SFD > 1.4 m were located in the Altai, Tianshan, and Pamir mountains (Fig. 3e). On the QTP, the SFD was approximately 0.59 m deeper than in eastern China at the same latitude and was clearly related to altitude. On the whole, the SFD increased approximately 0.13 m per degree of latitude in eastern China ($p < 0.01$, $R^2 = 0.80$) .

3.2. Temporal variations of the near-surface soil freeze state

In general, the FD was delayed by 10 ± 1 days with a rate of 0.20 ± 0.02 days/year across China over 50 years (1961–2010) (Fig. 4a). The changes in FD varied greatly for the three frozen ground regions (Fig. 5a). The rate of increase was higher in northwestern China (0.28 ± 0.04 days/year) than on the QTP (0.22 ± 0.03 days/year) and in eastern China (0.18 ± 0.03 days/year). The FD had an increasing trend in 286 of the 339 stations over the observation records considered in this study, with 178 stations exhibiting increasing trends that were significant at the $p < 0.1$ level, 155 stations at the $p < 0.05$ level, and 121 stations at the $p < 0.01$ level. However, significant decreasing trends were also detected over the study period, with 17 stations at the $p < 0.1$ level, 14 stations at the $p < 0.05$ level and 8 stations at the $p < 0.01$ level (Fig. 5a).

In this study, the LD was advanced by 18 ± 2 days with a rate of 0.36 ± 0.04 days/year across China over 50 years (1961–2010) (Fig. 4b). The changes in the LD varied greatly for the three frozen ground regions (Fig. 5b). The decrease rate was higher in eastern China (0.41 ± 0.05 days/year) than on the QTP (0.35 ± 0.03 days/year)

and in northwestern China (0.23 ± 0.03 days/year). The LD had a decreasing trend in 311 of the 339 stations over the study period, with 234 stations exhibiting decreasing trends that were significant at the $p < 0.1$ level, 211 stations at the $p < 0.05$ level, and 168 stations at the $p < 0.01$ level. However, significant increasing trends were also detected over the study period, with 10 stations at the $p < 0.1$ level, 7 stations at the $p < 0.05$ level and 3 stations at the $p < 0.01$ level (Fig. 5b).

The DR was shortened by 28 ± 2 days with a rate of 0.56 ± 0.04 days/year across China over 50 years (1961–2010) (Fig. 4c). The rate of decrease was significantly greater on the QTP (0.59 ± 0.04 days/year) than in eastern China (0.58 ± 0.05 days/year) and northwestern China (0.51 ± 0.05 days/year). Similarly, the NF was shortened by 23 ± 2 days with a rate of 0.45 ± 0.04 days/year across China from 1961 to 2010 (Fig. 4d). The rate of decrease in the NF was significantly larger on the QTP (0.48 ± 0.04 days/year) than in eastern China (0.45 ± 0.05 days/year) and northwestern China (0.42 ± 0.05 days/year). The DR had a decreasing trend in 319 of the 339 stations over the study period, with 250 stations exhibiting decreasing trends that were significant at the $p < 0.1$ level, 233 stations at the $p < 0.05$ level, and 204 stations at the $p < 0.01$ level. However, significant increasing trends were also detected over the study period, with 7 stations at the $p < 0.05$ level and 6 stations at the $p < 0.01$ level (Fig. 5c). Similarly, the NF had a decreasing trend in 311 of the 339 stations over the study period, with 258 stations exhibiting decreasing trends that were significant at the $p < 0.1$ level, 247 stations at the $p < 0.05$ level, and 218 stations at the $p < 0.01$ level. However, significant increasing trends for the NF were also detected over the study period with 7 stations at the $p < 0.05$ level and 4 stations at the $p < 0.01$ level (Fig. 5d).

The SFD decreased by 20 ± 3 cm at a rate of 0.41 ± 0.06 cm/year across China over 50 years (1961–2010) (Fig. 4e). The changes in the SFD varied greatly for the three frozen ground regions. The decrease rate was significantly larger on the QTP (0.47 ± 0.06 cm/year) than in eastern China (0.41 ± 0.06 cm/year) and northwestern China (0.34 ± 0.08 cm/year). The SFD had a decreasing trend in 292 of the 339 stations over the study period, with 220 stations exhibiting decreasing trends that were significant at the $p < 0.1$ level, 200 stations at the $p < 0.05$ level, and 154 stations at the $p < 0.01$ level. However, significant increasing trends were also detected over the study period, with 14 stations at the $p < 0.1$ level, 11 stations at the $p < 0.05$ level and 9 stations at the $p < 0.01$ level (Fig. 5e).

As shown in Fig. 4, the anomalies of LD, DR, NF and SFD changed slightly after the mid-1990s. This change was consistent with the observations that global temperature rise had grown slowly in the last ten years from 1999 to 2008 (Knight et al., 2009).

3.3. Variations of the near-surface soil freeze state with latitude and altitude

Although changes in the near-surface soil freeze state varied greatly over the study period across China (Fig. 5), a significant correlation between the change in five freeze variables and latitude (altitude) was detected in this study (Fig. 6).

On the QTP, a positive correlation between the increasing rate of the FD and station altitude ($r = 0.40$, $p < 0.1$) was detected, whereas significant negative correlations between the decrease rate of the LD and station altitude ($r = -0.47$, $p < 0.05$), the decrease rate of the NF and station altitude ($r = -0.44$, $p < 0.05$), the decrease rate of the SFD and station altitude ($r = -0.50$, $p < 0.01$) were also detected, respectively. Similarly, a positive correlation between the increasing rate of the FD and station altitude ($r = 0.33$, $p < 0.1$) was detected, whereas significant negative correlations between the decrease rate of the DR and station altitude ($r = -0.35$, $p < 0.05$), the decrease rate of the NF and station altitude ($r = -0.28$, $p < 0.1$), the decrease rate of the SFD and station altitude ($r = -0.35$, $p < 0.05$) were also detected in northwestern China, respectively. The above results indicate that
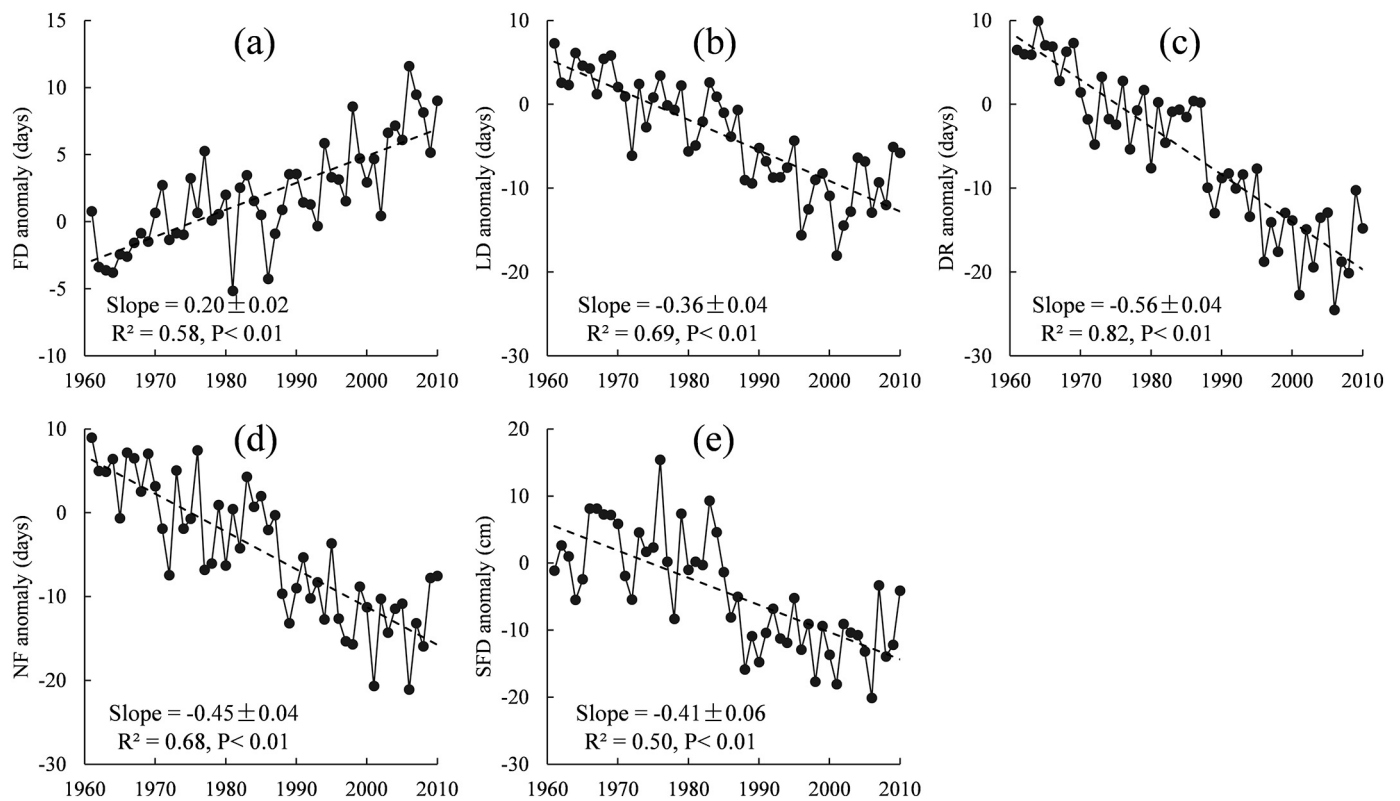
Fig. 4. Time series of anomalies for the five freeze variations (with respect to 1961 to 1990 mean) across China over 50 years (1961–2010).

changes in the near-surface soil freeze state are greater in high-altitude regions than those in low-altitudes.

In eastern China, a positive correlation between the increasing rate of the FD and station latitude ($r = 0.41$, $p < 0.01$) was detected, whereas significantly negative correlations between the decrease rate of the LD and station latitude ($r = -0.35$, $p < 0.01$), the decrease rate of the NF and station latitude ($r = -0.33$, $p < 0.01$), the decrease rate of the SFD and station latitude ($r = -0.64$, $p < 0.01$) were also detected, respectively. The above results indicate that changes in the near-surface soil freeze state are greater in high-latitude regions than those in low-latitudes.

4. Discussion

The results of this study indicate that the near-surface soil freeze state has changed significantly across China over 50 years (1961–2010). The FD was delayed with a rate of 0.20 ± 0.02 days/year across all of China, with rates of 0.18 ± 0.03 days/year, 0.28 ± 0.04 days/year, and 0.22 ± 0.03 days/year in eastern China, northwestern China and on the QTP, respectively. Similar results have been found in Indiana, USA (Sinha and Cherkauer, 2008), in Kansas, USA (Anandhi et al., 2013), in the Three Rivers Source Region, China (Luo et al., 2017), on the QTP, China (Guo and Wang, 2014; Li et al., 2012) and in all of China (Wang et al., 2015). On the basis of ground surface temperature data from 636 meteorological stations from 1956 to 2006, Wang et al. (2015) found that the FD of the near-surface soil freeze was delayed by approximately 0.10 days/year across China, which was only half of our results in this study (0.20 ± 0.02 days/year). From the Special Sensor Microwave/Imager data, Li et al. (2012) found that the FD was delayed by approximately 0.50 days/year on the QTP from 1988 to 2007, which was more than two times larger than our results (0.22 ± 0.02 days/year). From the Community Land Model and a suite of high-resolution atmospheric data, Guo and Wang (2014) noted that the FD was delayed by approximately 0.17 days/year on the QTP from 1981 to 2010, which was slightly lower than our results (0.22 ± 0.02 days/year). Luo et al.

(2017) pointed out that the delaying rate of the FD for the Three Rivers Source Region in China was approximately 0.32 days/year from 1960 to 2014, which was slightly larger than our results on the QTP (0.22 ± 0.02 days/year).

The LD of the near-surface soil freeze occurred nearly 0.36 ± 0.04 days/year earlier across China over the study period. A similar result has also been found in Kansas, USA (Anandhi et al., 2013) and several other regions. Wang et al. (2015) found that the LD of the near-surface soil freeze was advanced by approximately 0.15 days/year across China, which was less than half of our results (0.41 ± 0.05 days/year). Guo and Wang (2014) found that the LD of the near-surface soil freeze was advanced by approximately 0.47 days/year on the QTP, which was slightly larger than our results (0.35 ± 0.03 days/year). Luo et al. (2017) found that the decrease rate of the LD for the Three Rivers Source Region in China was consistent with our results on the QTP (0.35 ± 0.03 days/year).

In this study, the DR and NF decreased by 0.56 ± 0.04 and 0.45 ± 0.04 days/year across China over 50 years (1961–2010), respectively. Wang et al. (2015) found that the DR and NF decreased by 0.25 and 0.20 days/year from 1956 to 2006, respectively, which was significantly lower than our results. On the QTP, the number of freeze days decreased by 0.61 days/year during the period 1967–1997 (Zhao et al., 2004) and by 0.64 days/year during the period 1981–2010 (Guo and Wang, 2014), which was basically consistent with our results (0.59 ± 0.04 days/year). However, Li et al. (2012) found that the number of freeze days decreased by 1.68 days/year from 1988 to 2007, which was nearly three times larger than our result on the QTP (0.59 ± 0.04 days/year). Meanwhile, in the Three Rivers Source Region of China, the number of freeze days decreased by 0.75 days/year during the period 1960–2014 (Luo et al., 2017), which was slightly higher than our results on the QTP (0.59 ± 0.04 days/year).

The SFD decreased significantly at a rate of 0.41 ± 0.06 cm/year across China over 50 years (1961–2010), and the decrease rate was significantly higher on the QTP (0.47 ± 0.06 cm/year) than in eastern China (0.41 ± 0.06 cm/year) and northwestern China
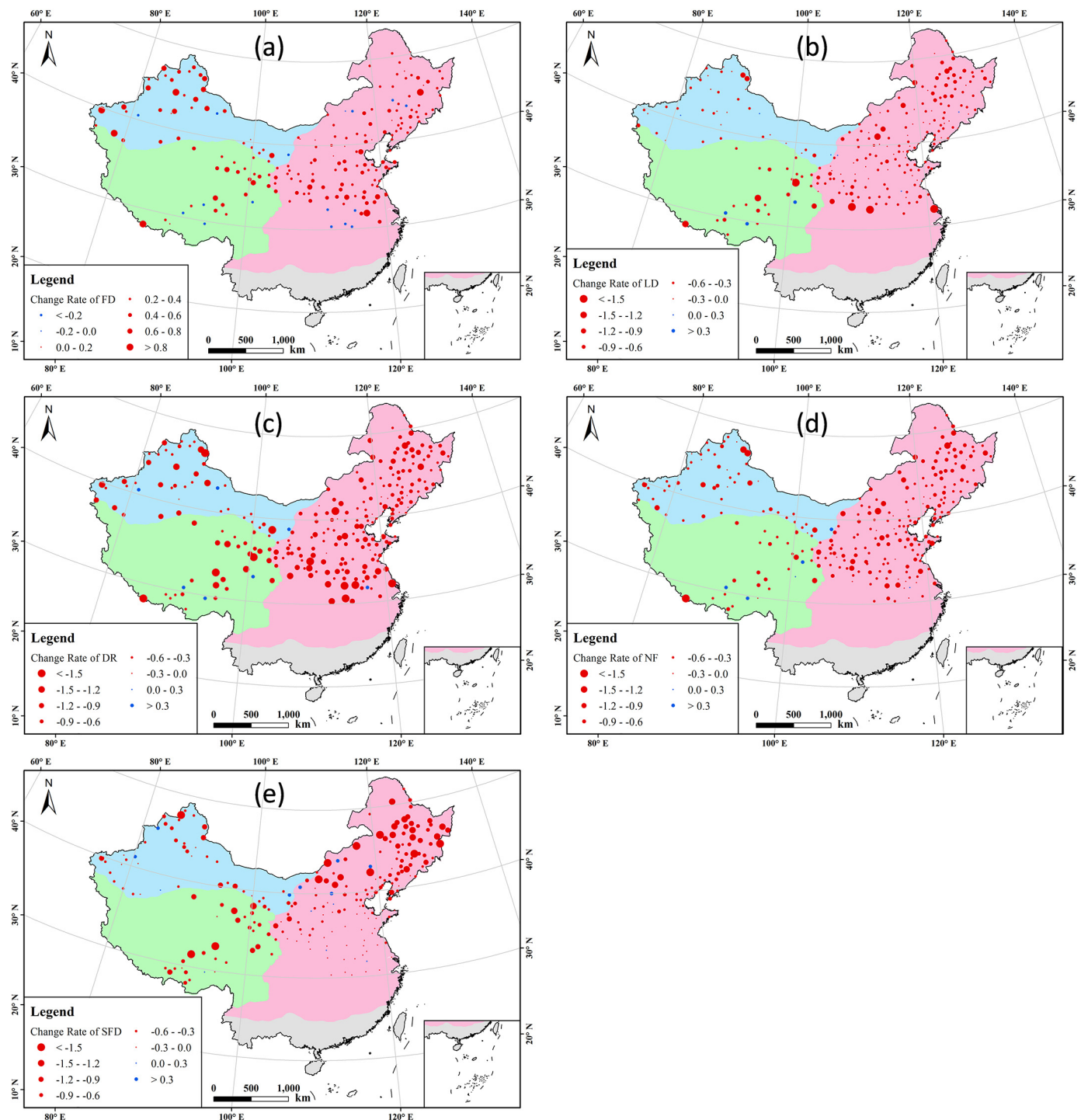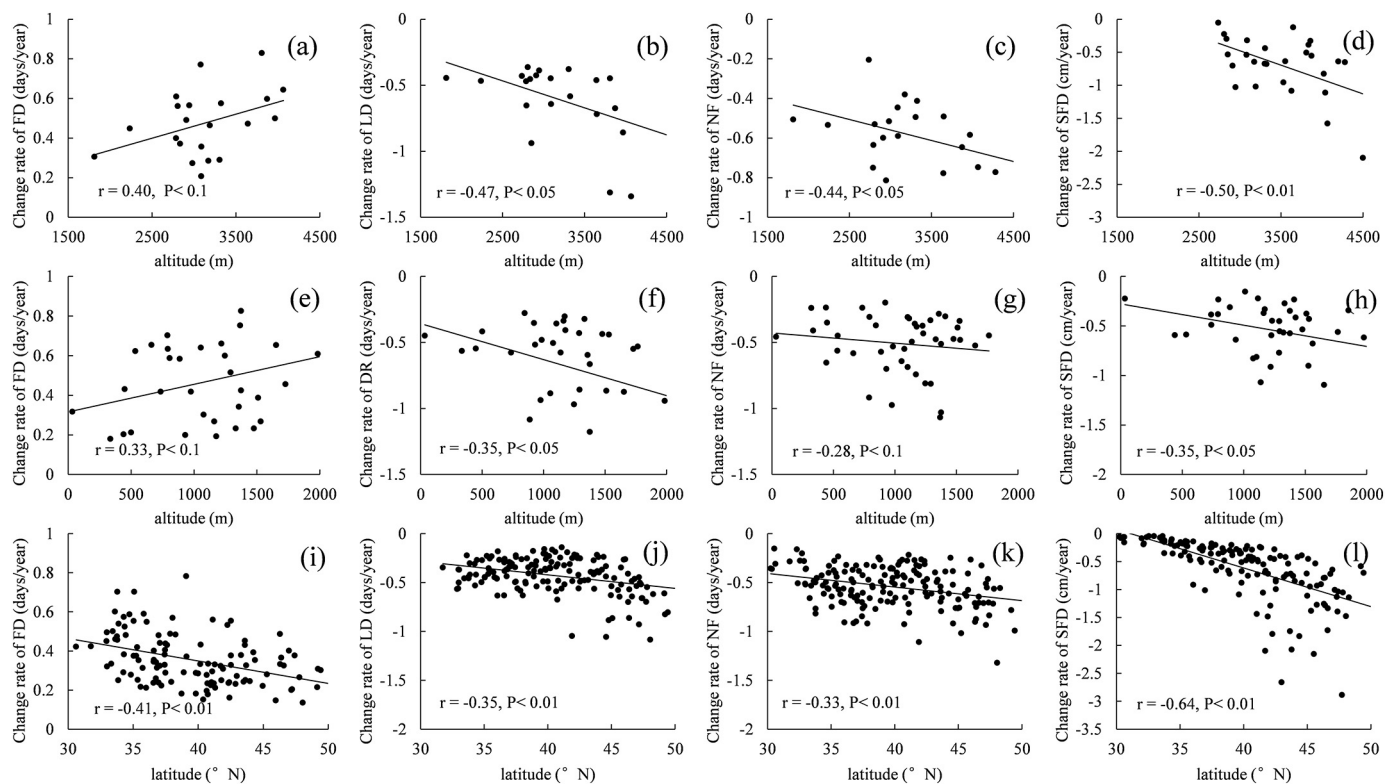
Fig. 5. Change rate of the five freeze variations for stations at the $p < 0.1$ level across China over 50 years (1961–2010). (a), (b), (c), (d) and (e) represent the trend of the FD (first date), LD (last date), DR (duration), NF (actual number of freeze days) and SFD (maximum seasonally frozen depth), respectively. The background in figure reflects the three frozen ground regions and non-frozen ground region.

$(0.34 \pm 0.08 \, \text{cm/year})$. From the Stefan solution and 845 meteorological data across China, Peng et al. (2017) found that the soil freeze depth decreased significantly at a rate of 0.18 cm/year, which was significantly lower than our results $(0.41 \pm 0.06 \, \text{cm/year})$. Meanwhile, the decrease rate of the SFD on the QTP (0.22 cm/year) was only half that of our results $(0.47 \pm 0.06 \, \text{cm/year})$, and that in northwestern China (0.26 cm/year) was slightly lower than our results $(0.34 \pm 0.08 \, \text{cm/year})$. From the daily freeze data of 50 meteorological stations on the QTP, Zhao et al. (2004) found that the decrease rate of SFD was approximately 0.44 cm/year, which largely

corresponds to our results on the QTP $(0.47 \pm 0.06 \, \text{cm/year})$. On the basis of observational soil freeze depth data from 14 meteorological stations in the Three Rivers Source Region of China during 1960 to 2014, Luo et al. (2017) found that the decrease rate of SFD was approximately 0.40 cm/year, which was slightly lower than our results on the QTP $(0.47 \pm 0.06 \, \text{cm/year})$.

In this study, the change trend of the near-surface soil freeze state was basically consistent with previous research, but the magnitude varied greatly for each variable. This may be mainly attributed to the different estimation methods or study periods. By using different

Fig. 6. Relation between the change rate of freeze variables and altitude (latitude). (a), (b), (c) and (d) represent the relation between altitude and the change rate of the FD, LD, NF and SFD on the QTP, respectively. (e), (f) (g) and (h) represent the relation between altitude and the change rate of the FD, DR, NF and SFD in northwestern China, respectively. (i), (j), (k) and (l) represent the relation between latitude and the change rate of the FD, LD, NF and SFD in eastern China, respectively. Each point represents one station. Only the correlation analyses passing the statistical tests at the $p < 0.1$ level were shown in this study.

Table 2
General information regarding the meteorological stations and estimated SFD from three methods.

Station code	Lon.(°E)	Lat.(°N)	Ele. (m)	Mean (cm)			Correlation	
				SS[a]	ST[b]	Ob[c]	SS-Ob	ST-Ob
52533	98.48	39.77	1477	98	128	99	0.7*	0.1
52546	99.83	39.37	1332	75	77	73	0.8*	0.3
52652	100.43	38.93	1483	91	126	95	0.6*	0.7*
52657	100.25	38.18	2787	207	233	206	0.6*	0.2
52661	101.08	38.80	1765	105	151	109	0.7*	0.1

[a] SS denotes that the Stefan solution was used to estimate the SFD.
[b] ST denotes that 0–320 cm soil temperature was used to estimate the SFD by linearly interpolating the depth of the 0 °C isotherm.
[c] Ob denotes the observed SFD from the China Meteorological Administration (CMA).
* The asterisk denotes that the correlation analyses passed the statistical tests at the p < 0.01 level.

estimation methods, we investigated the near-surface soil freeze state of five stations in the Qilian Mountains of western China from 1961 to 2007. For the mean SFD, the values from the Stefan solution were basically consistent with the observed ones, whereas those from the soil temperature at different depths were obviously larger than the observations (Table 2). The estimated SFDs from the Stefan solution had a high correlation with the observations, whereas those from soil temperature at different depths had almost no correlation with the observations (Table 2). For the mean DR and NF, the values from ground surface temperature (0 cm soil temperature) were obviously larger than the observations, whereas those from 5 cm soil temperature were obviously smaller than the observations. Similar results were also found for the FD and LD (Table 3).

The above comparisons at least partly reflect the diversity of factors affecting soil freeze. Wang et al. (2015) found that changes in the near surface soil freeze status across China were primarily controlled by changes in air temperature, but urbanization may also play an important role. Peng et al. (2017) found that vegetation growth was more strongly correlated with soil freeze depth, while snow depth was not

Table 3
Estimated mean FD, LD, NF and DR from three methods over the study period.[a]

Station	FD (days)			LD (days)			NF (days)			DR (days)		
	0 cm	5 cm	Ob	0 cm	5 cm	Ob	0 cm	5 cm	Ob	0 cm	5 cm	Ob
52533	15	74	54	264	192	212	209	105	132	249	118	157
52546	22	80	46	260	190	224	202	101	154	240	110	179
52652	25	78	52	259	186	213	197	99	133	235	108	162
52657	−34	63	36	294	203	245	260	131	193	329	140	210
52661	25	74	52	260	193	223	200	109	140	236	119	172

[a] The three estimation methods are based on daily soil temperature at 0 cm (ground surface temperature), daily soil temperature at 5 cm and daily soil freeze observations (Ob). To facilitate comparison, the base date is September 1st, and the FD and LD values are the number of days after the base date.

significant. Luo et al. (2017) found that the near surface soil freeze status for the Three Rivers Source Region was strongly affected by air temperature and soil moisture (liquid precipitation), but not by snow. Frauenfeld and Zhang (2011) thought that the near-surface soil freeze state was affected not only by air temperature but also by warm season precipitation, cold season snow cover, and site-specific soil properties.

5. Conclusions

The spatial distributions and temporal variations of the near-surface soil freeze state across China were estimated using the daily soil freeze observational data at 476 meteorological stations over 50 years from September 1, 1961 to August 31, 2011. We also compared the distributions and changes of the near-surface soil freeze state for the three frozen regions. The main conclusions can be summarized as follows.

The near-surface soil freeze state varied greatly across China. Comparisons of the three frozen ground regions show that the frozen ground region on the QTP has an earlier freeze, later thaw, longer freeze days, and deeper seasonally frozen depth. Meanwhile, the spatial distribution of the freeze state has a close relationship with geographic characteristics. The distributions of the near-surface soil freeze state can be explained largely by altitude in northwestern China and on the QTP, whereas they can be explained by latitude in eastern China.

The near-surface soil freeze state has changed significantly across China over 50 years. The first date of freezing was delayed by approximately 10 ± 1 days with a rate of 0.20 ± 0.02 days/year, the last date advanced by approximately 18 ± 2 days with a rate of 0.36 ± 0.04 days/year, the duration and the number of freeze days decreased by 28 ± 2 and 23 ± 2 days, with rates of 0.56 ± 0.04 and 0.45 ± 0.04 days/year, respectively, and the maximum seasonally frozen depth decreased by 20 ± 3 cm with a rate of 0.41 ± 0.06 cm/year. The significant correlation between the change rate of the freeze variables and latitude (altitude) indicate that the change rate for the near-surface soil freeze state is high in high-latitude and high-altitude regions.

Compared with previous research, the trend of the near-surface soil freeze state was largely consistent, but the magnitude varied greatly for each variable. This finding may be primarily attributed to the different estimation methods or study periods. Based on the 'true' soil freeze data across China, the results of this study may provide an important reference for analysing, contrasting and predicting the changes of the near-surface soil freeze state under the warming climate.

Acknowledgments

Declarations of interest

None.

References

China Meteorological Adminisitration (CMA), 2003. The Norm of Surface Meteorological Observation. China Meteorological Press.

Akerman, H.J., Johansson, M., 2008. Thawing permafrost and thicker active layers in subarctic Sweden. Permafr. Periglac. Process. 19 (3), 279–292.

Anandhi, A., et al., 2013. Long-term spatial and temporal trends in frost indices in Kansas, USA. Clim. Chang. 120 (1–2), 169–181.

Cheng, G., Jin, H., 2013. Permafrost and groundwater on the Qinghai-Tibet Plateau and in northeast China. Hydrogeol. J. 21 (1), 5–23.

Cherkauer, K.A., Lettenmaier, D.P., 1999. Hydrologic effects of frozen soils in the upper Mississippi River basin. J. Geophys. Res. Atmos. 104 (D16), 19599–19610.

Connon, R.F., Quinton, W.L., Craig, J.R., Hayashi, M., 2014. Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada.

Hydrol. Process. 28 (14), 4163–4178.

Cuo, L., et al., 2015. Frozen soil degradation and its effects on surface hydrology in the northern Tibetan Plateau. J. Geophys. Res. Atmos. 120 (16), 8276–8298.

Dobinski, W., 2011. Permafrost. Earth Sci. Rev. 108 (3), 158–169.

Frauenfeld, O.W., Zhang, T.J., 2011. An observational 71-year history of seasonally frozen ground changes in the Eurasian high latitudes. Environ. Res. Lett. 6 (4), 044024.

Frauenfeld, O.W., Zhang, T.J., Barry, R.G., Gilichinsky, D., 2004. Interdecadal changes in seasonal freeze and thaw depths in Russia. J. Geophys. Res. 109 (D5), D05101.

Fyodorov-Davydov, D.G., et al., 2008. Seasonal thaw of soils in the north Yakutian ecosystems. In: 9th International Conference on Permafrost. Institute of Northern Engineering, University of Alaska, Fairbanks, pp. 481–486.

Guo, D., Wang, H., 2014. Simulated change in the near-surface soil freeze/thaw cycle on the Tibetan Plateau from 1981 to 2010. Chin. Sci. Bull. 59 (20), 2439–2448.

Henry, H.A.L., 2008. Climate change and soil freezing dynamics: historical trends and projected changes. Clim. Chang. 87 (3–4), 421–434.

Hinzman, L.D., Kane, D.L., Gieck, R.E., Everett, K.R., 1991. Hydrologic and thermal properties of the active layer in the Alaskan Arctic. Cold Reg. Sci. Technol. 19 (2), 95–110.

IPCC, 2014. Observations: Cryosphere, Climate Change 2013-the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jin, H., et al., 2007. Degradation of permafrost in the Xing'anling Mountains, northeastern China. Permafr. Periglac. Process. 18 (3), 245–258.

Jones, P.D., Hulme, M., 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. Int. J. Climatol. 16 (4), 361–377.

Karlsson, J.M., Lyon, S.W., Destouni, G., 2012. Thermokarst lake, hydrological flow and water balance indicators of permafrost change in Western Siberia. J. Hydrol. 464 (465), 459–466.

Knight, J., et al., 2009. Do global temperature trends over the last decade falsify climate predictions? Bull. Am.Meteorol.Soc. 90 (8), 22–23.

Li, X., Jin, R., Pan, X., Zhang, T., Guo, J., 2012. Changes in the near-surface soil freeze–thaw cycle on the Qinghai-Tibetan Plateau. Int. J. Appl. Earth Observ. Geoinform. 17 (1), 33–42.

Luo, S., Fang, X., Lyu, S., Jiang, Q., Wang, J., 2017. Interdecadal changes in the freeze depth and period of frozen soil on the three Rivers Source Region in China from 1960 to 2014. Adv. Meteorol. 2017 (5), 1–14.

Mazhitova, G.G., 2008. Soil temperature regimes in the discontinuous permafrost zone in the east European Russian Arctic. Eur. Soil Sci. 41 (1), 48–62.

McCauley, C.A., White, D.M., Lilly, M.R., Nyman, D.M., 2002. A comparison of hydraulic conductivities, permeabilities and infiltration rates in frozen and unfrozen soils. Cold Reg. Sci. Technol. 34 (2), 117–125.

Menzel, A., Jakobi, G., Ahas, R., Scheifinger, H., Estrella, N., 2003. Variations of the climatological growing season (1951–2000) in Germany compared with other countries. Int. J. Climatol. 23 (7), 793–812.

Mu, C., et al., 2015. Editorial: organic carbon pools in permafrost regions on the Qinghai-Xizang (Tibetan) Plateau. Cryosphere 9 (2), 479–486.

Peng, X., et al., 2016. Response of changes in seasonal soil freeze/thaw state to climate change from 1950 to 2010 across China. J. Geophys. Res. Earth Surf. 121 (11), 1984–2000.

Peng, X., et al., 2017. Response of seasonal soil freeze depth to climate change across China. Cryosphere 11 (3), 1–33.

Sinha, T., Cherkauer, K.A., 2008. Time series analysis of soil freeze and thaw processes in Indiana. J. Hydrometeorol. 9 (5), 936–950.

Wang, C., Jin, S., Wu, Z., Yang, C., 2009. Evaluation and application of the estimation methods of frozen (thawing) depth over China. Adv. Earth Science 24 (2), 132–140.

Wang, G., Mao, T., Chang, J., Du, J., 2014. Impacts of surface soil organic content on the soil thermal dynamics of alpine meadows in permafrost regions: data from field observations. Geoderma 232, 414–425.

Wang, K., Zhang, T., Zhong, X., 2015. Changes in the timing and duration of the near-surface soil freeze/thaw status from 1956 to 2006 across China. Cryosphere 8 (4), 3785–3809.

Wu, Q.B., Zhang, T.J., 2010. Changes in active layer thickness over the Qinghai-Tibetan Plateau from 1995 to 2007. J. Geophys. Res. Atmos. 115, D09107.

Zhang, T., Barry, R.G., Knowles, K., Heginbottom, J.A., Brown, J., 1999. Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere. Polar Geogr. 23 (2), 147–169.

Zhang, T., Barry, R.G., Knowles, K., Ling, F., Armstrong, R.L., 2003. Distribution of seasonally and perennially frozen ground in the Northern Hemisphere. In: Phillips, M., Springman, S.M., Arenson, L.U. (Eds.), Proceedings of the 8th International Conference on Permafrost, 21–25 July 2003. A.A. Balkema, Lisse, the Netherlands, Zurich, Switerland, pp. 1289–1294.

Zhao, L., et al., 2004. Changes of climate and seasonally frozen ground over the past 30 years in Qinghai–Xizang (Tibetan) Plateau, China. Glob. Planet.Change 43 (1–2), 19–31.

Zhao, L., Wu, Q.B., Marchenko, S.S., Sharkhuu, N., 2010. Thermal state of permafrost and active layer in central Asia during the international polar year. Permafr. Periglac. Process. 21 (2), 198–207.

Zhou, Y., Guo, D., Qiu, G., Cheng, G., Li, S., 2000. Geocryology in China. Science Press (450pp.).

Zhou, Z., et al., 2015. Responses of alpine grassland to climate warming and permafrost thawing in two basins with different precipitation regimes on the Qinghai-Tibetan Plateaus. Arct. Antarct. Alp. Res. 47 (1), 125–131.

Zimov, S.A., Chapin, F.S., 2006. Permafrost and the global carbon budget. Science 312 (5780), 1612–1613.